NASA
MFS-
pt.2
c.1

NASA TECHNICAL TRANSLATION

NASA TT F-257

TECH LIBRARY KAFB, NM
0062952

NASA TT F-257

MAGNETIC FIELD OF SUNSPOTS – PART II

by L. E. Gurevich and A. I. Lebedinskiy

From *Zhurnal Eksperimental'noy i Teoreticheskoy Fiziki,*
Vol. 16, No. 9, 1946.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1965

TECH LIBRARY KAFB, NM
0062952

NASA TT F-257

MAGNETIC FIELD OF SUNSPOTS - PART II

By L. E. Gurevich and A. I. Lebedinskiy

Translation of "Magnitnoye pole solnechnykh pyaten. II."
Zhurnal Eksperimental'noy i Teoreticheskoy Fiziki,
Vol. 16, No. 9, pp. 840-848, 1946.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 - Price $1.00

MAGNETIC FIELD OF SUNSPOTS. Part II

L. E. Gurevich and A. I. Lebedinskiy

Section 1. Equation of Circulation in the Presence of Hall Currents

In Part I (Ref. 1), we discussed the mechanism of self-excitation of the magnetic field of a spot. We confined ourselves to the discussion of a case in which the Hall currents perpendicular to the electric field were negligible compared to the currents parallel to it. In the present article we shall consider a general case, i.e., assume that the density of the electric field i is related to the electric field E and magnetic field H as follows:

$$\mathbf{i} = \sigma\mathbf{E} + \sigma'\mathbf{E}\times\mathbf{H}. \tag{1.1}$$

Here σ is the coefficient of electrical conductivity and σ' is the Hall coefficient. The ratio of these coefficients

$$\frac{\sigma}{\sigma'} = H_0 \tag{1.2}$$

has the dimension of a magnetic field. We shall see further that the Hall currents are insignificant at $H < H_0$, and, conversely, play a predominant part when $H > H_0$. As a result of the motion of an ionized gas in a magnetic field H at velocity v, its charged particles are subjected to a Lorentz force equivalent to the electric field.

$$\mathbf{E} = \frac{\mathbf{v}}{c}\times\mathbf{H}. \tag{1.3}$$

Substituting this expression into (1.1), we have

$$\mathbf{i} = \frac{\sigma}{c}\mathbf{v}\times\mathbf{H} + \frac{\sigma'}{c}(\mathbf{v}\times\mathbf{H})\times\mathbf{H}$$

or

$$\mathbf{i} = \frac{\sigma}{c}\mathbf{v}_\perp\times\mathbf{H} - \frac{\sigma'}{c}\mathbf{H}^2\mathbf{v}_\perp, \tag{1.4}$$

where $\mathbf{v}_\perp$ is the velocity component perpendicular to the magnetic field.

Expressions (1.1) and (1.3) are the most general formulas for the electric current and electric field in the presence of a magnetic field. In the most general case,

$$\mathbf{i} = \sigma\mathbf{E} + \sigma'\mathbf{E}\times\mathbf{H} + \sigma''\mathbf{H}(\mathbf{E}\cdot\mathbf{H}) \tag{1.5}$$

and

$$\mathbf{E} = \frac{\mathbf{v}}{c}\times\mathbf{H} - \frac{1}{c}\frac{\partial\mathbf{A}}{\partial t}. \tag{1.6}$$

The third term in (1.5) represents the current resulting from the focusing effect of the magnetic field, and the second term in (1.6) represents the "field of self-induction", i.e., an electric field resulting when the current changes with time. Here A is the vector potential related to the magnetic field by the equality /841

$$H = \text{curl } A.$$

In the region of the spot where the magnetic field (and its vector potential may be considered quasi-stationary, the second term in (1.6) vanishes. The electric field is then perpendicular to the magnetic field, and the focusing term in (1.5) is equal to zero.

In Part I, we have shown that although, strictly speaking, each sunspot constitutes a nonstationary circulation, in a spot which has existed for a long time the magnetic field may be considered stationary to a good approximation.

The general equation of motion of the gas in the spot is as follows:

$$\rho\frac{d\mathbf{v}}{dt} = \rho\left[\frac{\partial\mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right] = \mathbf{f} + \mathbf{F} = \mathbf{f} + \frac{\mathbf{i}}{c}\times\mathbf{H}, \tag{1.7}$$

where f is the hydrodynamic force and F is the electromagnetic force.

Let us write the component of this equation along the magnetic field and in the direction perpendicular to the magnetic field:

$$\left.\begin{aligned}\rho\left[\frac{\partial\mathbf{v}_\parallel}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}_\parallel\right] &= \mathbf{f}_\parallel,\\ \rho\left[\frac{\partial\mathbf{v}_\perp}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}_\perp\right] &= \mathbf{f}_\perp + \frac{\mathbf{i}}{c}\times\mathbf{H}.\end{aligned}\right\} \tag{1.7a}$$

In the longitudinal direction, the electromagnetic force is absent, and its influence on the transverse motion is exerted only indirectly, since the left side of the first equation of (1.7a) includes the total velocity v equal to

$$\mathbf{v} = \mathbf{v}_\parallel + \mathbf{v}_\perp.$$

In the second equation of (1.7a), we can assume the left side to be small compared to each term of the right side and thus neglect it, as was done in the preceding work. This means that the electromagnetic force F balances out the transverse part of the hydrodynamic force $\mathbf{f}_\perp$, so that we have

$$\mathbf{f}_\perp = -\frac{\mathbf{i}}{c} \times \mathbf{H}. \tag{1.8}$$

Substituting into the right side the expression for i (1.4), we obtain

$$\mathbf{f}_\perp = \frac{\sigma H^2}{c^2} \mathbf{v}_\perp + \frac{\sigma' H^2}{c^2} \mathbf{v}_\perp \times \mathbf{H}. \tag{1.9}$$

This equation is easy to solve with respect to $\mathbf{v}_\perp$. We shall introduce the following designations:

$$\left.\begin{aligned} a &= \frac{\sigma H^2}{c^2}, \\ b &= \frac{\sigma' H^2}{c^2}, \end{aligned}\right\} \tag{1.10}$$

so that

$$\mathbf{f}_\perp = a\mathbf{v}_\perp + b\mathbf{v}_\perp \times \mathbf{H}. \tag{1.9}$$

Multiplying this equation vectorially by H,

$$\mathbf{f}_\perp \times \mathbf{H} = a\mathbf{v}_\perp \times \mathbf{H} - b\mathbf{H}^2\mathbf{v}_\perp. \tag{1.11}$$

we now solve (1.9) with respect to $\mathbf{v}_\perp \cdot \mathbf{H}$: /842

$$\mathbf{v}_\perp \times \mathbf{H} = \frac{1}{b}(\mathbf{f}_\perp - a\mathbf{v}_\perp)$$

and substitute into (1.11):

$$\mathbf{f}_\perp \times \mathbf{H} = \frac{a}{b}(\mathbf{f}_\perp - a\mathbf{v}_\perp) - bH^2\mathbf{v}_\perp,$$

whence

$$\mathbf{v}_\perp = \frac{a\mathbf{f}_\perp - b\mathbf{f}_\perp \times \mathbf{H}}{a^2 + b^2H^2}. \tag{1.12}$$

This is the general expression for the transverse velocity $\mathbf{v}_\perp$ in any stationary magnetic field H. If the magnetic field is weak, i.e.,

$$H \ll \frac{a}{b} = \frac{\sigma}{\sigma'} = H_0$$

(see (1.2)), then, according to (1.1), the Hall current is small compared to the ordinary current and

$$\mathbf{v}_\perp = \frac{1}{a}\mathbf{f}_\perp = \frac{c^2\mathbf{f}_\perp}{\sigma H^2}. \tag{1.13}$$

This is the result of the preceding article (Ref. 1).

In the opposite limiting case $H \gg H_0$, when the Hall current is large,

$$\mathbf{v}_\perp = -\frac{1}{bH^2}\mathbf{f}_\perp \times \mathbf{H} = -\frac{c^2}{\sigma' H^4}\mathbf{f}_\perp \times \mathbf{H}. \tag{1.14}$$

In order of magnitude, the ratio of the transverse velocities is in both cases

$$\frac{v_\perp^{(1)}}{v_\perp^{(2)}} \approx \frac{\sigma' H}{\sigma} = \frac{H}{H_0}, \tag{1.15}$$

where $v_\perp^{(1)}$ and $v_\perp^{(2)}$ are the transverse velocities in both cases.

The density of the electric current may be expressed indirectly through hydrodynamic force $\mathbf{f}_\perp$ and magnetic field H. To this end, we multiply (1.8) vectorially by H:

$$\mathbf{f}_\perp \times \mathbf{H} = -\frac{1}{c}(\mathbf{i}\times\mathbf{H})\times\mathbf{H} = \frac{1}{c}[\mathbf{H}^2\mathbf{i} - (\mathbf{H}\mathbf{i})\mathbf{H}].$$

However, according to (1.4), i is perpendicular to H, and thus

$$\mathbf{i} = \frac{c}{H^2}\mathbf{f}_\perp \times \mathbf{H} = \frac{c}{H^2}\mathbf{f}\times\mathbf{H}. \tag{1.16}$$

The same result is obtained if expression (1.12) for the transverse velocity is substituted into (1.4).

Substituting expression (1.16) for i into the equation

$$\operatorname{curl}\mathbf{H} = \frac{4\pi}{c}\mathbf{i},$$

we obtain the equation for the magnetic field: /843

$$\operatorname{curl}\mathbf{H} = \frac{4\pi}{H^2}\mathbf{f}\times\mathbf{H}. \tag{1.17}$$

According to (1.3) and (1.12), the electric field in the spot is

$$\mathbf{E} = \frac{\mathbf{v}}{c}\times\mathbf{H} = \frac{\mathbf{v}_\perp}{c}\times\mathbf{H} = \frac{1}{c}\frac{1}{a^2+b^2H^2}(a\mathbf{f}_\perp\times\mathbf{H} + bH^2\mathbf{f}_\perp). \tag{1.18}$$

Finally, the Joule heat evolved by the current,

$$q = i \cdot E$$

becomes, after substitution of (1.16) and (1.18),

$$q = \frac{af_\perp^2}{a^2 + b^2H^2}. \tag{1.19}$$

According to (1.12), this may be written as

$$q = \mathbf{f}_\perp \mathbf{v}_\perp. \tag{1.20}$$

Hence, the Joule heat is determined exclusively by the motions of the gas and the hydrodynamic forces perpendicular to the magnetic field. The motion of the gas along the magnetic fields of force does not induce an electric current and therefore takes place without losses.

Section 2. Quantitative Estimates

In order to arrive at some definite physical conclusions from the formulas of the preceding section, it is necessary to determine the value of the coefficients σ and σ' and the critical field H_0.

The first quantity which can be estimated is the time (or length) of the free path of electrons τ. It depends on the number of electrons per unit volume n, the temperature T, and the effective cross section s for collisions of electrons with ions, electrons and atoms.

We shall first evaluate n as a function of T, assuming radiative equilibrium.

The equation of radiant energy balance is

$$-\frac{d}{dz}\lambda T^4 = \varkappa \rho F, \tag{2.1}$$

where z is the vertical coordinate, λ is the Stefan-Boltzmann constant, F is the density of the radiant energy flux, ρ is the mass density, and $\varkappa$ is the absorption coefficient calculated per unit mass. According to Chandrasekhar (Ref. 2), for a strongly ionized pure-hydrogen atmosphere,

$$\varkappa = \alpha \frac{\rho}{T^{7/2}}, \tag{2.2}$$

where

$$\alpha = 1.67 \cdot 10^{30}. \tag{2.3}$$

On the other hand, the condition of hydrostatic equilibrium, which is adequately met in the spot, gives

$$\frac{dp}{dz} = -\rho g. \tag{2.4}$$

Dividing (2.1) by (2.4), we have /844

$$\frac{d}{dp} T^4 = \frac{\varkappa F}{\lambda g} = \frac{\alpha F}{\lambda g} \frac{\rho}{T^{9/2}}. \tag{2.5}$$

However,

$$\rho = \frac{\frac{1}{2} m}{k} \frac{p}{T}, \tag{2.6}$$

where $k = 1.38 \cdot 10^{-16}$ is Boltzmann's constant, and $\frac{1}{2} m$ is the average mass of the gas particle, which in completely ionized hydrogen is equal to one-half the mass of the atom. Substituting (2.6) into (2.5) and integrating, we obtain

$$T^{19/2} - T_0^{19/2} = \frac{19}{32} \frac{\alpha F m}{g \lambda k} (p^2 - p_0^2). \tag{2.7}$$

Let T_0 and p_0 be the values corresponding to the depth at which hydrogen is completely ionized, i.e., $T_0 \sim 15{,}000$. Then, at temperatures $T > 30{,}000$, T_0 and p_0 can be rejected, and

$$p = \frac{32}{19} \left(\frac{g \lambda k}{\alpha F m} \right)^{1/2} T^{19/4},$$

and

$$n = \frac{p}{2kT} = \left(\frac{8 g \lambda}{19 k \alpha F m} \right)^{1/2} T^{15/4}. \tag{2.8}$$

Since

$$\left.\begin{aligned} g &= 2.7 \cdot 10^4, \\ \lambda &= 5.77 \cdot 10^{-5}, \\ k &= 1.38 \cdot 10^{-16}, \\ \alpha &= 1.67 \cdot 10^{30}, \\ F &= 6 \cdot 10^{10}, \\ m &= 1.67 \cdot 10^{-24}, \end{aligned}\right\} \tag{2.9}$$

we have

$$n = \beta T^{15/4}, \tag{2.10}$$

where

$$\beta = 0.168. \tag{2.11}$$

We can now estimate time τ of the free path of electrons. We have

$$\frac{1}{\tau} = nv(s_i + s_e), \tag{2.12}$$

where s_i and s_e are cross sections of collisions of electrons with ions and electrons.

According to Ref. 3, the cross section is equal to

$$s = \gamma\left(\frac{e^2}{kT}\right)^2, \tag{2.13}$$

where

$$\gamma = 2\pi \ln\left[\frac{1}{\sqrt{8\pi n}}\left(\frac{3kT}{2e^2}\right)^{3/2}\right] \tag{2.14}$$

depends slightly on n and T. According to (2.10)

$$\gamma = \pi \ln \frac{27k^3}{64\pi e^6 \beta} - \frac{3\pi}{4}\ln T = \\ = 38.5 - 2.35 \ln \frac{T}{10000}. \tag{2.15}$$

/845

Hence it is obvious that γ is practically independent of temperature in the range under consideration, from tens to hundreds of thousands of degrees. At T = 50,000°, the value γ = 34.25, and for this reason we shall further assume that

$$\gamma = 34. \tag{2.16}$$

Thus,

$$s = 34\left(\frac{e^2}{kT}\right)^2 = \frac{0.96 \cdot 10^{-4}}{T^2}. \tag{2.17}$$

The electron velocity is

$$v = \sqrt{\frac{8kT}{\pi m}} = 1.97 \cdot 10^6 \sqrt{T}. \tag{2.18}$$

Consequently, the time of the free path is

$$\tau = \frac{1}{nvs} = \frac{3.14 \cdot 10^{-2}}{T^{3/2}}, \tag{2.19}$$

and the free path length is

$$l = \frac{1}{ns} = \frac{6.2 \cdot 10^4}{T^{1/4}}.$$

The neglect of the gas-kinetic cross sections of atoms and ions for collisions with electrons is justified, because up to $T \approx 10^6$, the Coulomb cross section is greater than the gas-kinetic cross section of the neutral atom. Moreover, this neglect would be also valid at higher temperatures, since the atoms are then stripped of their outermost electrons, and their gas-kinetic cross section becomes still smaller.

Let us now estimate the coefficients of electrical conductivity of σ and σ'. Generally speaking, these coefficients depend on the magnetic field. A rigorous theory of this dependence is exposed, for example, in the work of Davydov (Ref. 4). In order to clarify the physical meaning of the formulas used later, we shall carry out an elementary and non-rigorous derivation.

Let us consider the motion of an electron acted upon by an electric field E, by a magnetic field H, and by collisions with other particles whose influence we shall represent schematically by the friction force $\zeta \mathbf{v}$, proportional to the velocity. The equation of motion is

$$m\dot{\mathbf{v}} = e\mathbf{E} + e\frac{\mathbf{v}}{c} \times \mathbf{H} - \zeta \mathbf{v}.$$

The coefficient ζ is estimated on the basis of the argument that in the absence of an electric and magnetic field, the velocity v should be extinguished during time τ of the free path. Hence, $\zeta = m/\tau$, and therefore the equation of stationary motion is

$$e\mathbf{H} + e\frac{\mathbf{v}}{c} \times \mathbf{H} - \frac{m}{\tau}\mathbf{v} = 0.$$

Let E be directed along axis x and H along axis y. Then, by solving this equation with respect to the components, we have

$$v_x = \frac{cEH}{H^2 + H_0^2},$$

where

$$v_y = \frac{cH_0 E}{H^2 + H_0^2}, \qquad (2.20)$$

$$H_0 = \frac{mc}{e\tau}.$$

/846

The density of the electric field is known to be

$$i_x = env_x = \frac{enc\,H_0}{H^2 + H_0^2} E = \sigma E,$$

$$i_z = env_z = \frac{enc}{H^2 + H_0^2} EH = \sigma' EH,$$

whence

$$\left.\begin{aligned} \sigma &= \frac{enc\,H_0}{H^2 + H_0^2}, \\ \sigma' &= \frac{enc}{H^2 + H_0^2}. \end{aligned}\right\} \qquad (2.21)$$

Several conclusions follow from these formulas. So long as the magnetic field is weak, i.e., when $H \ll H_0$, the coefficients σ and σ' are almost independent of H and may be considered equal to their values of σ and σ' in the absence of the field. In the opposite limiting case of a very strong field defined by the inequality $H \gg H_0$, the quantities σ and σ' are

$$\left.\begin{aligned} \sigma &= \sigma_0 \left(\frac{H_0}{H}\right)^2, \\ \sigma' &= \sigma'_0 \left(\frac{H_0}{H}\right)^2. \end{aligned}\right\} \qquad (2.22)$$

Finally

$$\frac{\sigma}{\sigma'} = H_0,$$

so that the quantity H_0 introduced into (1.2) has the value (2.20).

These conclusions of the elementary theory differ only slightly from the rigorous theory. In particular, in the limiting case of strong fields, we actually have

$$H_0 = \frac{8}{3} \frac{mc}{e\tau}, \qquad (2.23)$$

i.e., only a numerical factor 8/3 appears, which does not change our estimates of the order of magnitude.

We are now able to make all the necessary estimates. Substituting (2.19) into (2.23), we have

$$H_0 = \frac{8}{3} \frac{mc}{e\tau} = 4.78 \cdot 10^{-6}\ T^{1/4}. \qquad (2.24)$$

Further, on the basis of (2.10), (2.17), (2.21) and (2.28), the electrical conductivity σ_0 in the absence of a magnetic field is

$$\sigma_0 = \frac{enc}{H_0} = 0.5 \cdot 10^6 \, T^{3/2}, \qquad (2.25)$$

and the Hall coefficient in a weak magnetic field is

$$\sigma_0' = \frac{\sigma_0}{H_0} = \frac{1.05 \cdot 10^{11}}{T^{3/2}}. \qquad (2.26)$$ /847

On the basis of the above formulas, the following table has been calculated:

T / 10 000°	n	H_0	σ_0	σ_0'
0,6	$2,5 \cdot 10^{13}$	$1,5 \cdot 10^{3}$	$2,3 \cdot 10^{11}$	$1,5 \cdot 13^{8}$
1,0	$1,7 \cdot 10^{14}$	$4,8 \cdot 10^{3}$	$5 \cdot 10^{11}$	$1,05 \cdot 10^{8}$
3,0	$1,05 \cdot 10^{16}$	$5,6 \cdot 10^{4}$	$2,6 \cdot 10^{12}$	$4,6 \cdot 10^{7}$
5,0	$7,1 \cdot 10^{17}$	$1,8 \cdot 10^{5}$	$5,6 \cdot 10^{12}$	$3,1 \cdot 10^{7}$
10,0	$9,6 \cdot 10^{17}$	$8,5 \cdot 19^{5}$	$1,6 \cdot .0^{13}$	$1,9 \cdot 10^{7}$
50,0	$3,9 \cdot 10^{20}$	$3,2 \cdot 10^{7}$	$1,8 \cdot 15^{14}$	$5,6 \cdot 10^{6}$
100,0	$5,3 \cdot 10^{21}$	$1,5 \cdot 10^{8}$	$5 \cdot 10^{14}$	$3,3 \cdot 15^{6}$

Commas in this table represent decimal points.

These figures are in sharp disagreement with the results of Cowling (Ref. 5), although our final formulas for the computation of σ_0, σ_0' and H_0 differ only slightly from those cited in his work. This pronounced discrepancy is due only to a discrepancy in the values of n. Cowling does not indicate, and we were not able to understand, how he obtained these values of n.

When our table is examined, it should be kept in mind that the figures pertaining to the outer layers, i.e., the first two lines, constitute only a very rough estimate, since in deriving the relation between x and T we have assumed that hydrogen is completely ionized and that formula (2.2) applies.

This table leads to the conclusion that in the outer layers of the spot the magnetic field is comparable to H_0, and therefore the Hall currents are substantial. The field increases with the depth, but H_0 does so also.

In the previous work, we showed that the depth of the spot is no less than $2 \cdot 10^4$ km. At this depth, the temperature of the atmosphere

reaches $(1.5 - 2)\cdot 10^5$ degrees, and H_0 is of the order of 10^7 gauss.

The upper limit of the magnetic field strength in the spot, calculated in the same work, was found to be 30,000 gauss, and hence, in the deep parts of the spot the field is much lower than critical, and the Hall currents are negligibly small. The fact that in the previous work we assumed x = const and that in this article we consider x to be a function of temperature is of no importance because the allowance for the change of x with temperature produces only a slight rise in the lower limit of the spot depth and only a slight decrease in the upper limit of the possible value of H.

In the absence of Hall currents, the electric field in the spot is horizontal and is directed at each point along a circle with its center on the axis of the spot. In the presence of Hall currents, there appears a radial component of the electric field. The electric field does not exceed a few hundredths of a volt per centimeter and for this reason cannot produce a Stark effect.

The Joule losses determined from formula (1.19) at $H \ll H_0$, are

equal to

$$q = \frac{f_\perp^2}{a} = \frac{c^2 f_\perp^2}{\sigma H^2}.$$

However, it was shown in Part I that

$$f_\perp \approx \frac{H^2}{8\pi R},$$

where R is the size of the spot. This means that

$$q = \frac{c^2 H^2}{64\pi^2 \sigma R^2} = \frac{H^2/8\pi}{2t_0},$$

where

$$t_0 = \frac{4\pi\sigma R^2}{c^2} \approx \frac{R}{v_\perp}.$$

In Part I (see formula (3.17)), it was shown that t_0 is the time for /848

the establishment of a stationary field in the spot and hence, the magnetic energy of the spot takes approximately the same time to convert into heat.

Leningrad State University

Received
25 November, 1945

References

1. Gurevich, L. E., Lebedinskiy, A. I. ZhETF, Vol. 16, No. 9, p. 832; DAN SSSR (in press).
2. Chandrasekhar. Proc. Roy. Soc. A. 135, 472, 1931.
3. Gurevich, L. E. Osnovy fizicheskoy kinetiki (Principles of Chemical Kinetics), GITTL, p. 162, 1940.
4. Davydov, B. I. ZhETF, Vol. 7, 1069, 1937.
5. Cowling, T. G. Monthly Not. Roy. Astr. Soc., 93, 90, 1932.

Translated for the National Aeronautics and Space Administration by John F. Holman and Co. Inc.

NASA-Langley, 1965 F-257

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546